Parton Propagation and Fragmentation in QCD Matter

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Introduction: perturbative QCD

- Asymptotic freedom: At short distances QCD is a weekly coupled theory (quarks and gluons are free). But how to connect to hadronic observables?

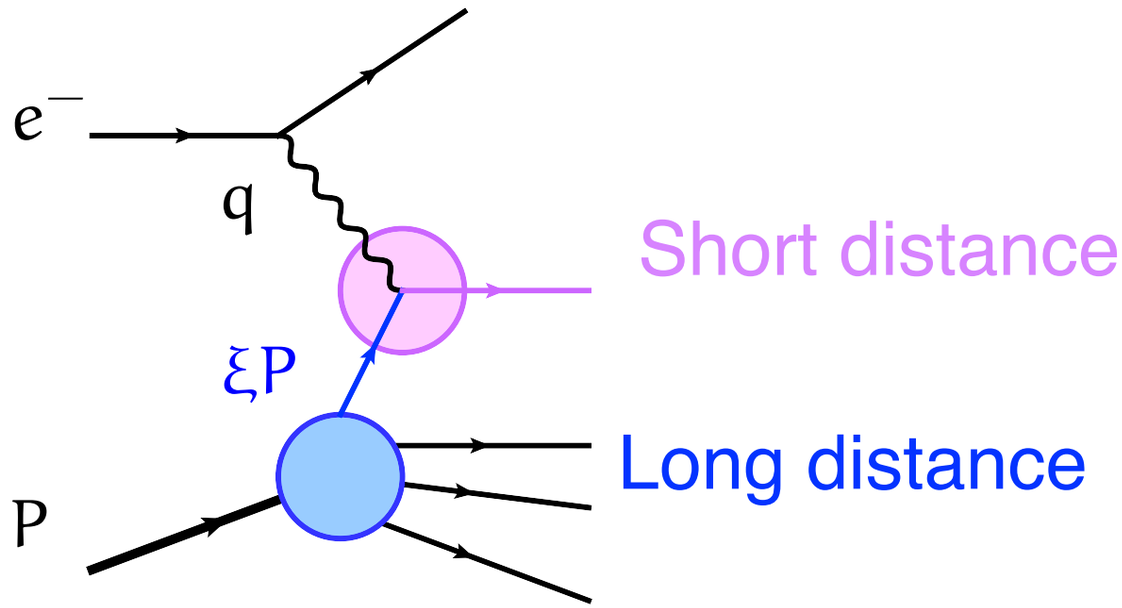
- Factorization theorems: One can factorize short distance physics (calculable) from large distance non-perturbative physics encoded in universal (process independent) parton distributions (PDF's, Fragmentation functions). Exp: DIS, Drell-Yan, hadron production, etc.

- RG description: Resummation of collinear/soft logarithms. Observables are independent of factorization scale.

- Some (inclusive) observables are collinear and infrared safe (not sensitive to non-perturbative physics). Exp: $e^+ e^-$ total cross section, Jet shapes, etc

Deep-Inelastic Scattering

- Use a well known projectile (cf. photon, Z, W) to probe the structure of the proton (nuclei)



Lorentz invariants:

$$Q^2 = -q^2 > 0$$

$$x = \frac{Q^2}{2P \cdot q}$$

- QCD Factorization: the hadronic tensor reads

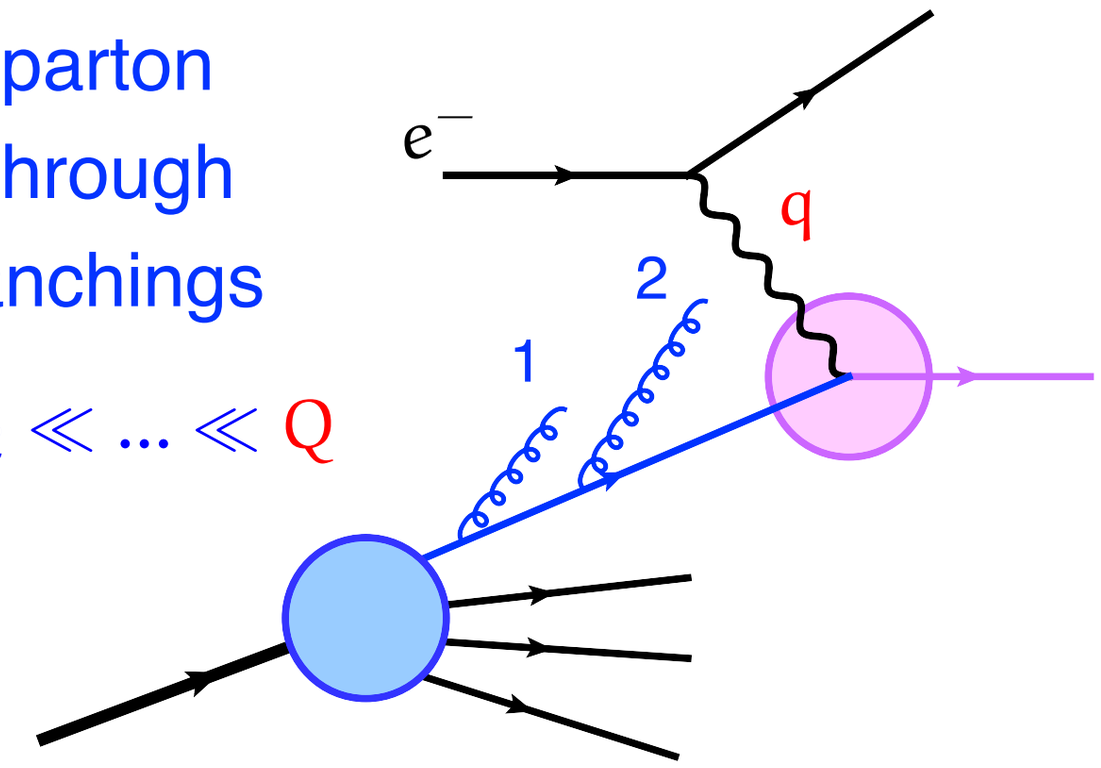
$$W^{\mu\nu}(q,P) = \sum_a \int_x^1 \frac{d\xi}{\xi} f_{a/A}(\xi,\mu)\, H_a^{\mu\nu}(q,\xi P,\mu,\alpha_s(\mu)) + \mathcal{O}\left(\frac{m_N^2}{Q^2}\right)$$

Higher twist suppressed in the Bjorken limit $Q^2 \to \infty$

Deep-Inelastic Scattering

evolution of parton distribution through collinear branchings

$\mu_0 \ll k_{\perp 1} \ll k_{\perp 2} \ll \ldots \ll Q$



If no final state measured: no collinear logs

- DGLAP (RG evolution) $\mu \dfrac{d}{d\mu} W^{\mu\nu}(q, P) = 0$

$$\mu \frac{d}{d\mu} f_{a/A}(\xi, \mu) = \sum_b \int_\xi^1 \frac{d\xi'}{\xi'} P_{a/b}(\xi')\, f_{b/A}(\xi/\xi', \mu)$$

- Resums large (collinearly enhanced) logs $\alpha_s \ln \dfrac{Q^2}{\mu_0}$

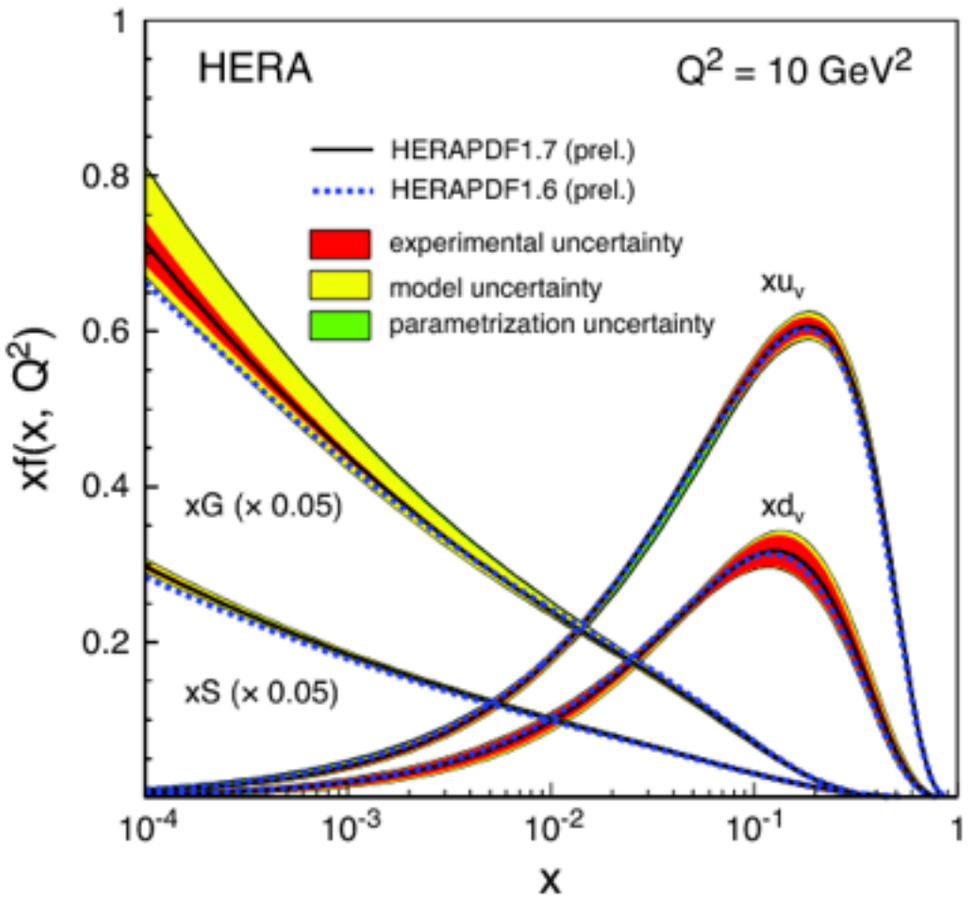
Initial state interactions at high energy:
parton propagation in cold nuclear matter

DIS: high energy and large nuclei

- At small x the gluon distribution increases exponentially (gluons dominate the dynamics)

- Higher twist corrections enhance at small x and for large nuclei A

$$\mathcal{O}\left(\frac{m_N^2}{Q^2}\right) \rightarrow \mathcal{O}\left(\frac{m_N^2}{Q^2} A^{1/3} x^{-\lambda}\right)$$

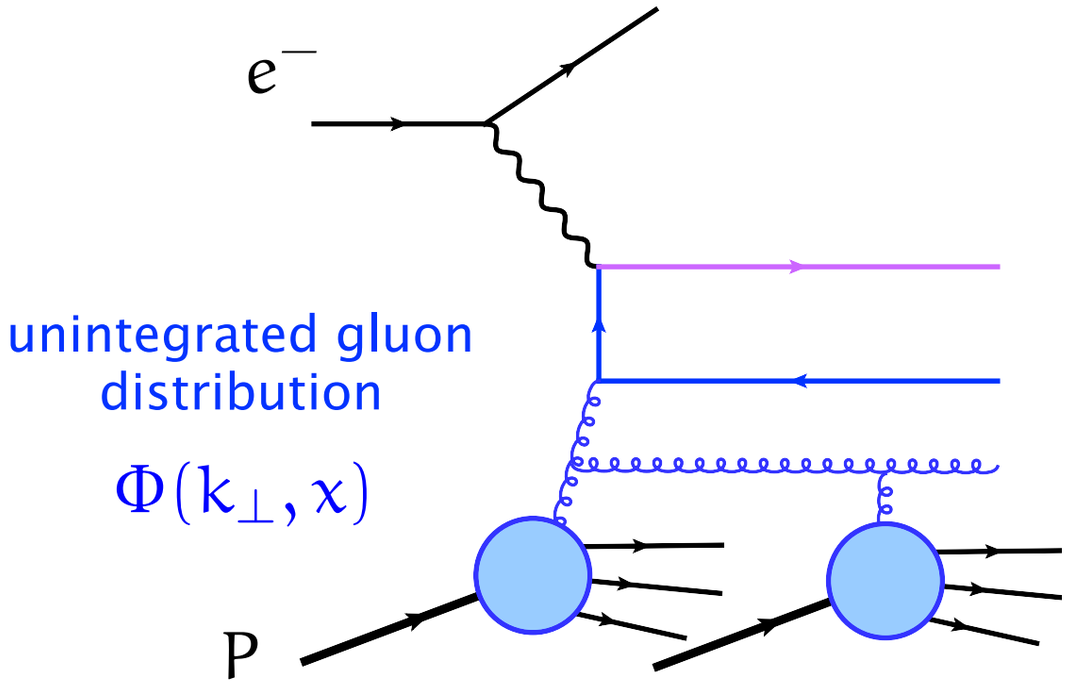


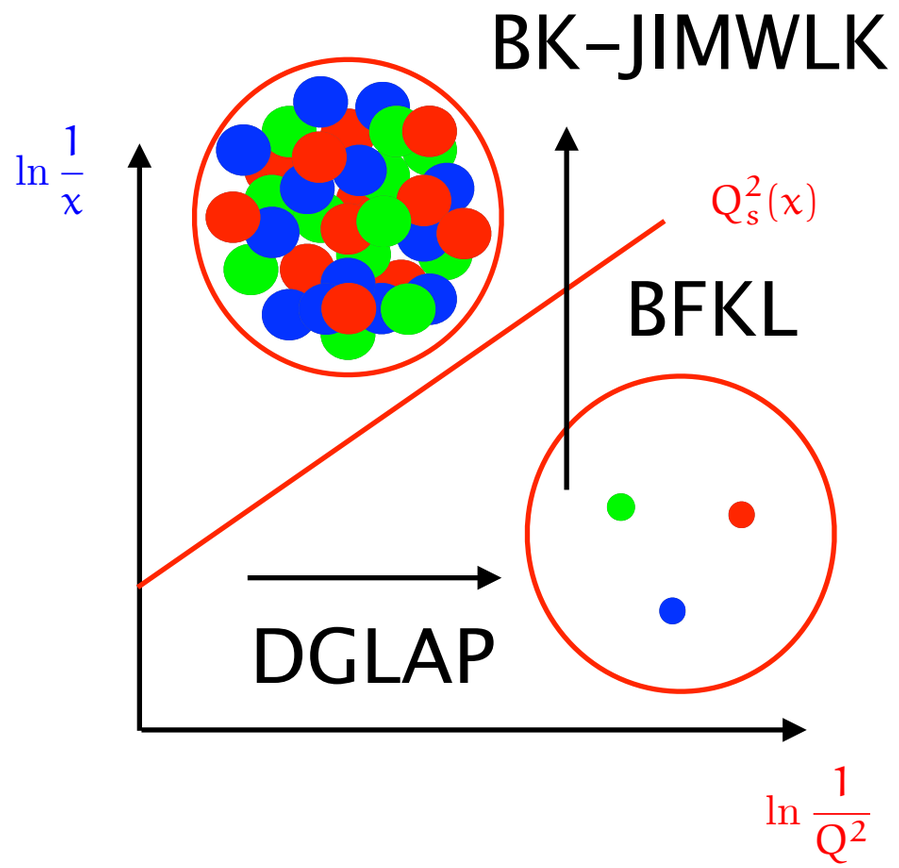
- Regge limit more adequate

$$s \rightarrow \infty \ (x \rightarrow 0) \qquad Q^2 \text{ fixed}$$

Gluon saturation: high energy and large systems

[Mueller, Qiu (1986) McLerran, Venugopalan (1994) Balitsky (1996) Kovchegov (1997), Kovner, Leonidov, Weigert, Jalilian-Marian, Iancu, McLerran (1996-2001)]





- CGC: kt-factorization + gluon recombination and rescattering
- BK-JIMWLK + MV: resum powers of:

$\alpha_s \ln \frac{1}{x}$ and $\alpha_s A^{1/3}$

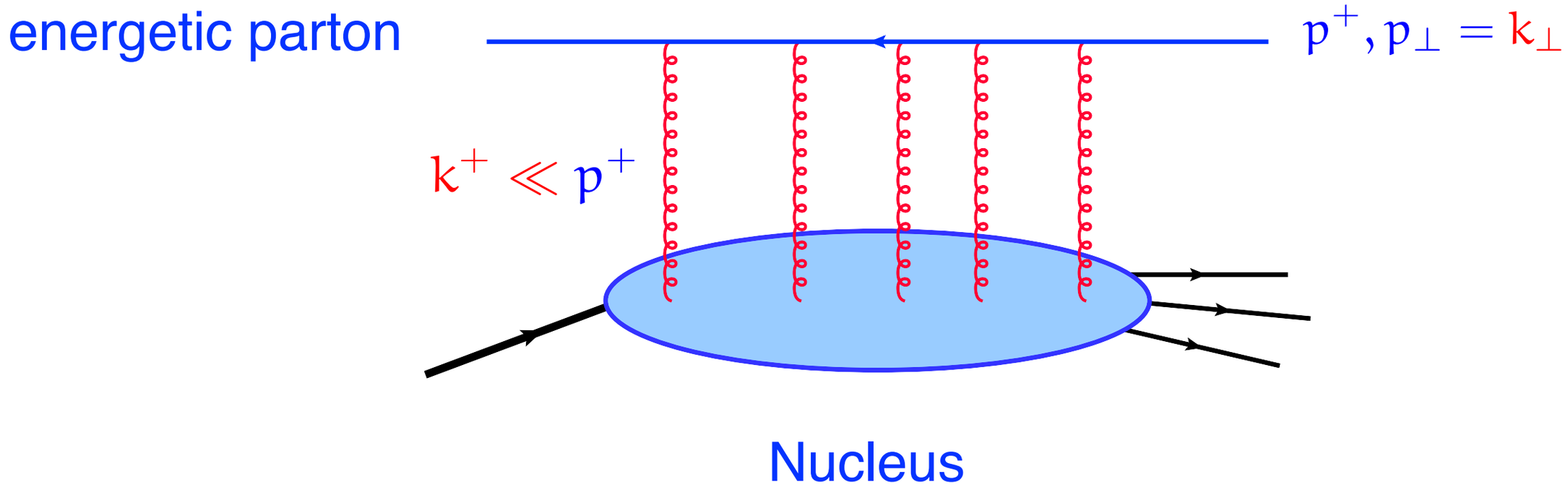
- Saturation scale

$$Q_s(x)^2 \sim m_N^2 \, A^{1/3} \, x^{-\lambda}$$

High energy parton propagation

- Large gluon occupancy $\Rightarrow$ strong classical fields $A^\mu \sim \frac{1}{g}$
- Relevant degrees of freedom are Wilson lines: eikonal propagation of high energy partons in nuclear matter

$$U(\boldsymbol{x}) \equiv \mathcal{P}\, \exp\left(ig \int_0^L dx^+ A^-(\boldsymbol{x}, x^+) \right)$$



High energy parton propagation

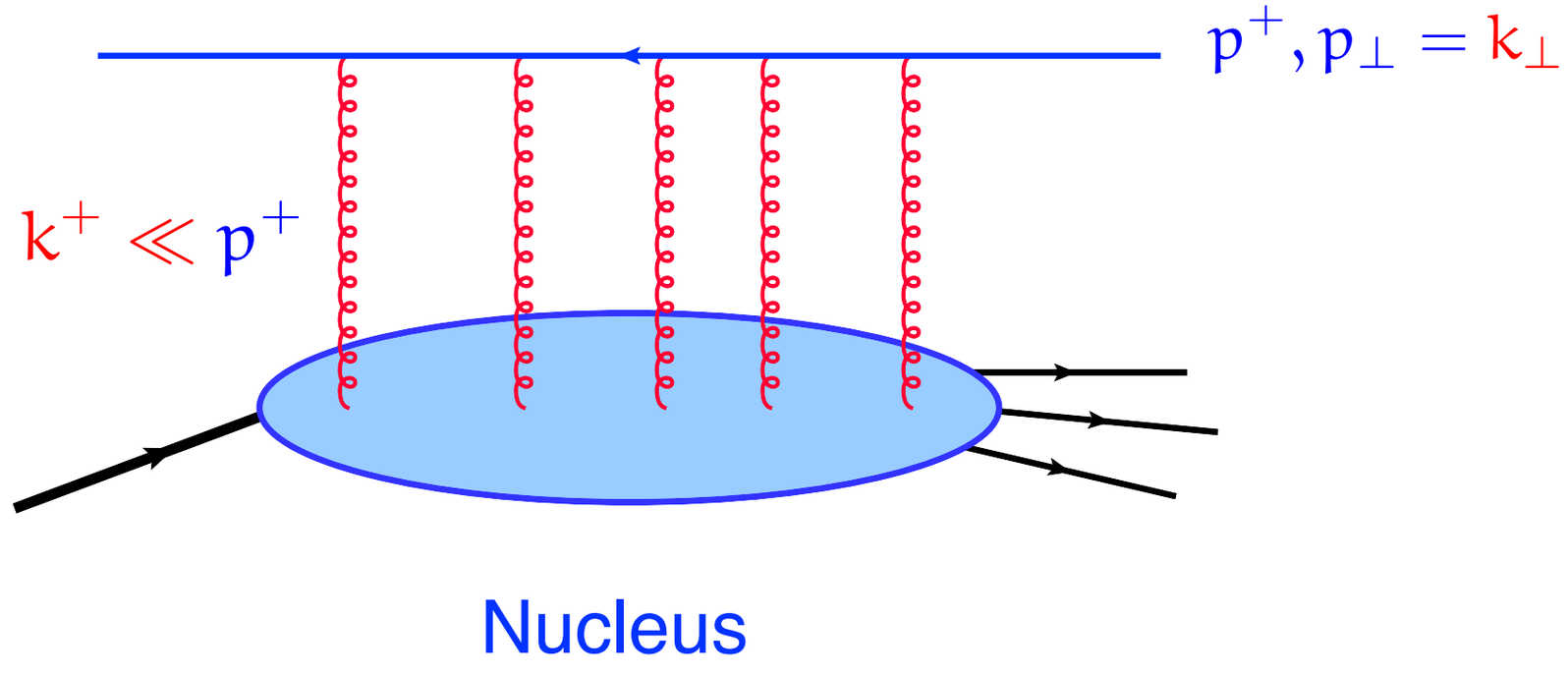
- Initial state interactions: unintegrated parton distribution in the saturation regime (DIS, p-A collisions)

unintegrated gluon-distribution $\Phi(\mathbf{k},\mathbf{x}) \equiv \mathbf{k}^2 \int \mathrm{d}^2\mathbf{x} \langle \mathrm{tr} U^\dagger(\mathbf{x}) U(0) \rangle_A \, e^{i\mathbf{x}\cdot\mathbf{k}}$

- Final state interactions: Jet propagation in cold/hot nuclear matter, jet-quenching in nucleus-nucleus collisions

pt-broadening probability $\mathbf{P}(\mathbf{k}) \equiv \int \mathrm{d}^2\mathbf{x} \langle \mathrm{tr} U^\dagger(\mathbf{x}) U(0) \rangle_{\mathrm{QGP}} \, e^{i\mathbf{x}\cdot\mathbf{k}}$

energetic parton



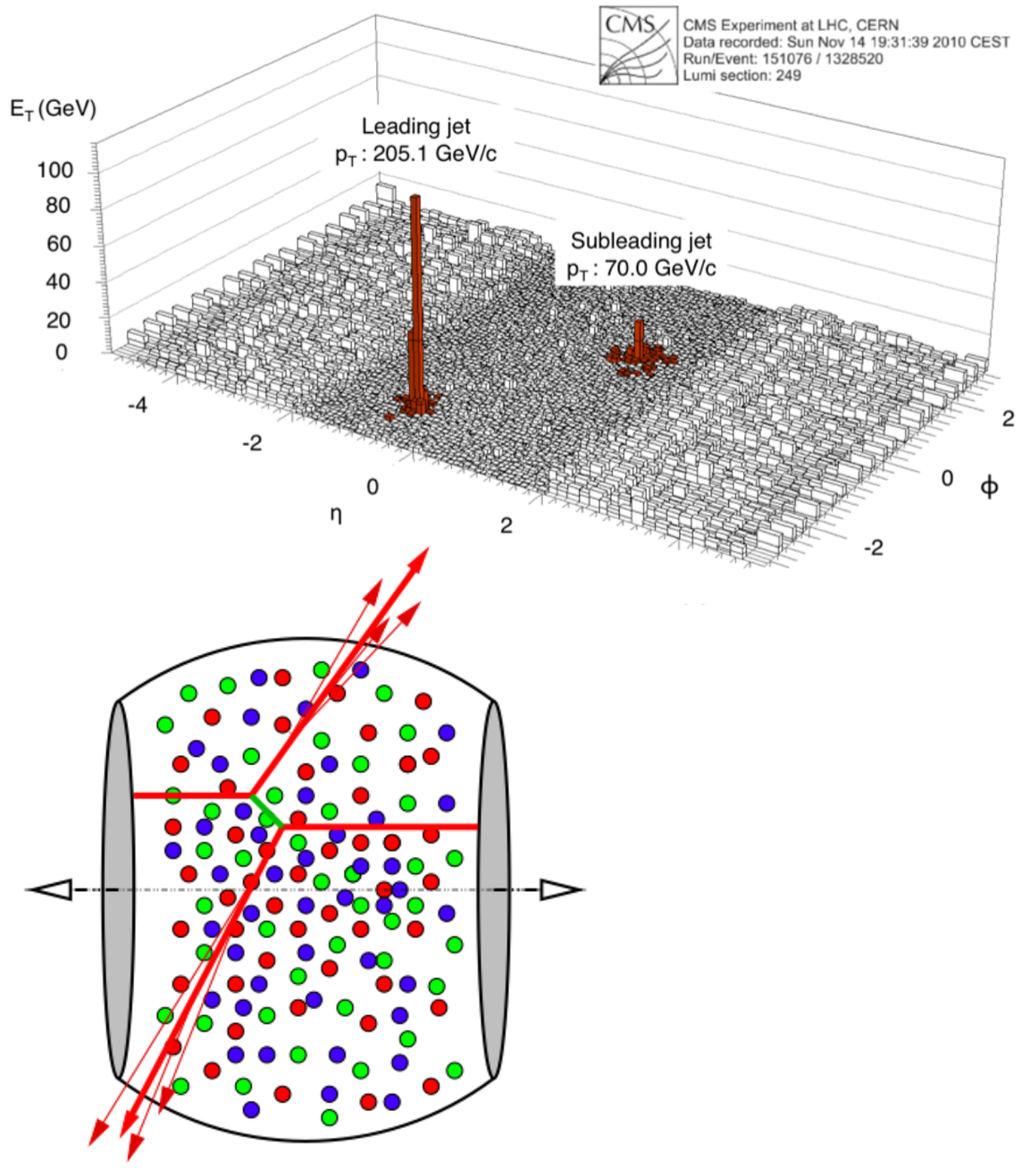
Final state interactions:

Modified fragmentation in the presence of QCD medium

Jets in HIC at the LHC

Jet-quenching :

a tool to probe the Quark-Gluon-Plasma and QCD dynamics at high parton density



Fragmentation in vacuum

- Intrajet distribution: Fragmentation functions are universal as long as final state interactions are suppressed. Higher twist corrections negligible.
- Interjet activity: soft gluon are radiated at late times coherently (interferences) off initial state and final state partons: color connexion, soft factors, angular ordering, etc.
- Coherence and color flow essential in hadronization models: cluster, string, dipole, etc.

Fragmentation in vacuum (intrajet evolution)

[Bassetto, Ciafaloni, Marchesini, Mueller, Dokshitzer, Khoze, Troyan,… 1980's]

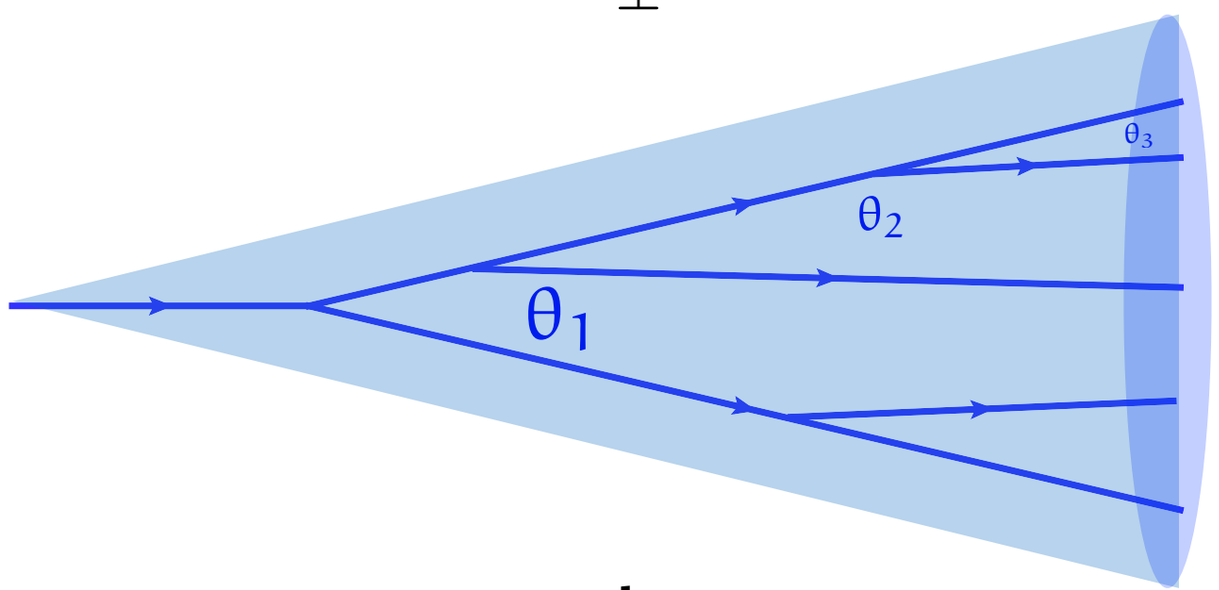
The jet is a coherent object, at each step of the cascade the total color charge is conserved: successive branchings are ordered in angles (destructive inferences for large angle gluon radiation)

$$\theta_{jet} > \theta_1 > \ldots > \theta_n$$

$$\frac{1}{E} < t_{\rm form} \sim \frac{\omega}{k_\perp^2} \qquad t_{\rm hadr} \sim \frac{E}{Q_0^2}$$

Jet virtuality

$Q \equiv E\,\theta_{jet}$

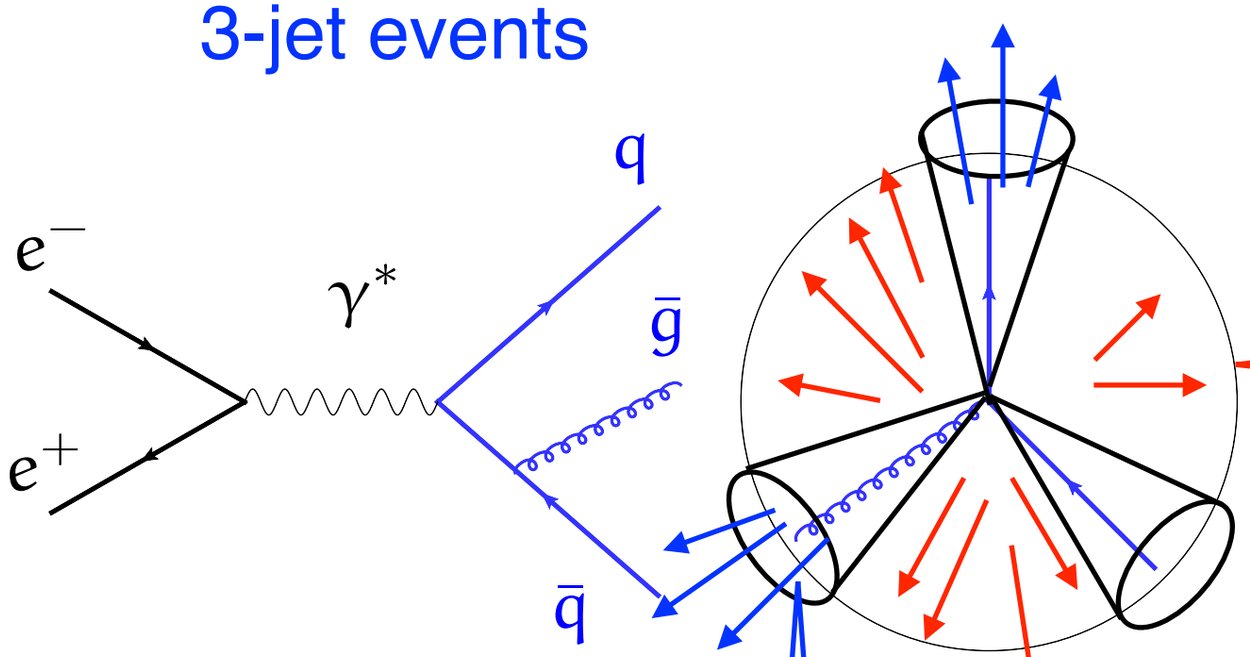


$Q_0 \sim \Lambda_{QCD}$

Color coherence in electron-positron annihilation

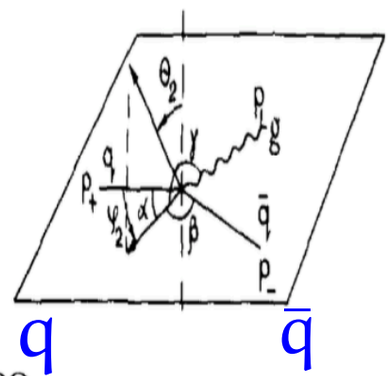
[Azimov, Dokshitzer, Khoze, Troyan (1985)]

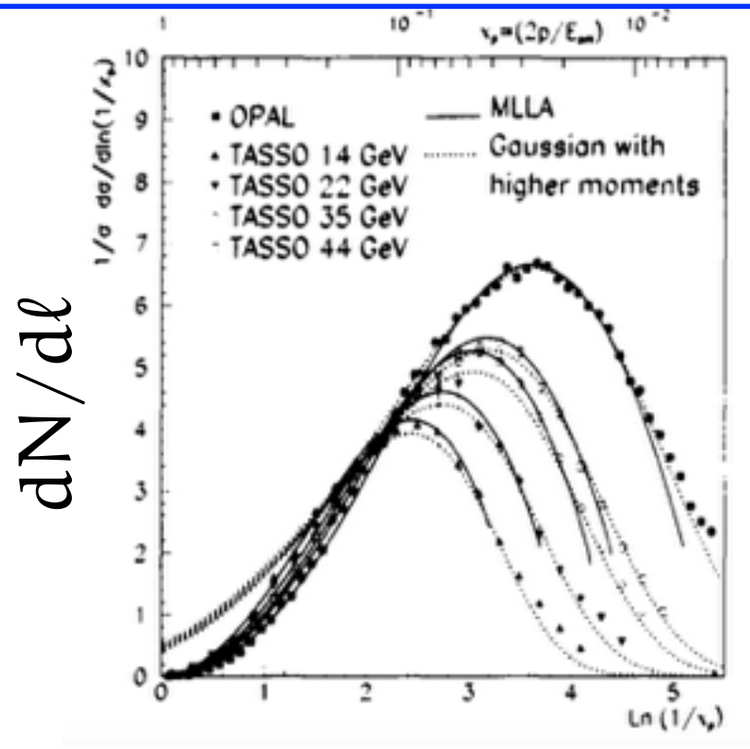
3-jet events



Interjet hadronic activity:
Dragg effect: "stringy" fragmentation from QCD

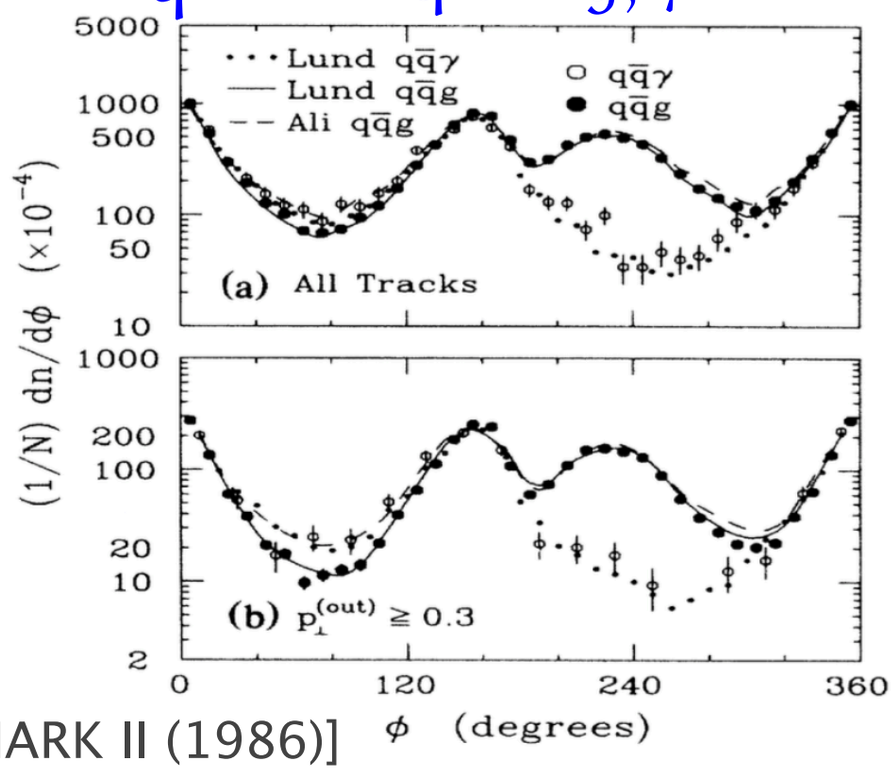
Fragmentation fct: intrajet dist





$dN/d\ell$

$$\ell = \ln \frac{1}{z}$$



[MARK II (1986)]

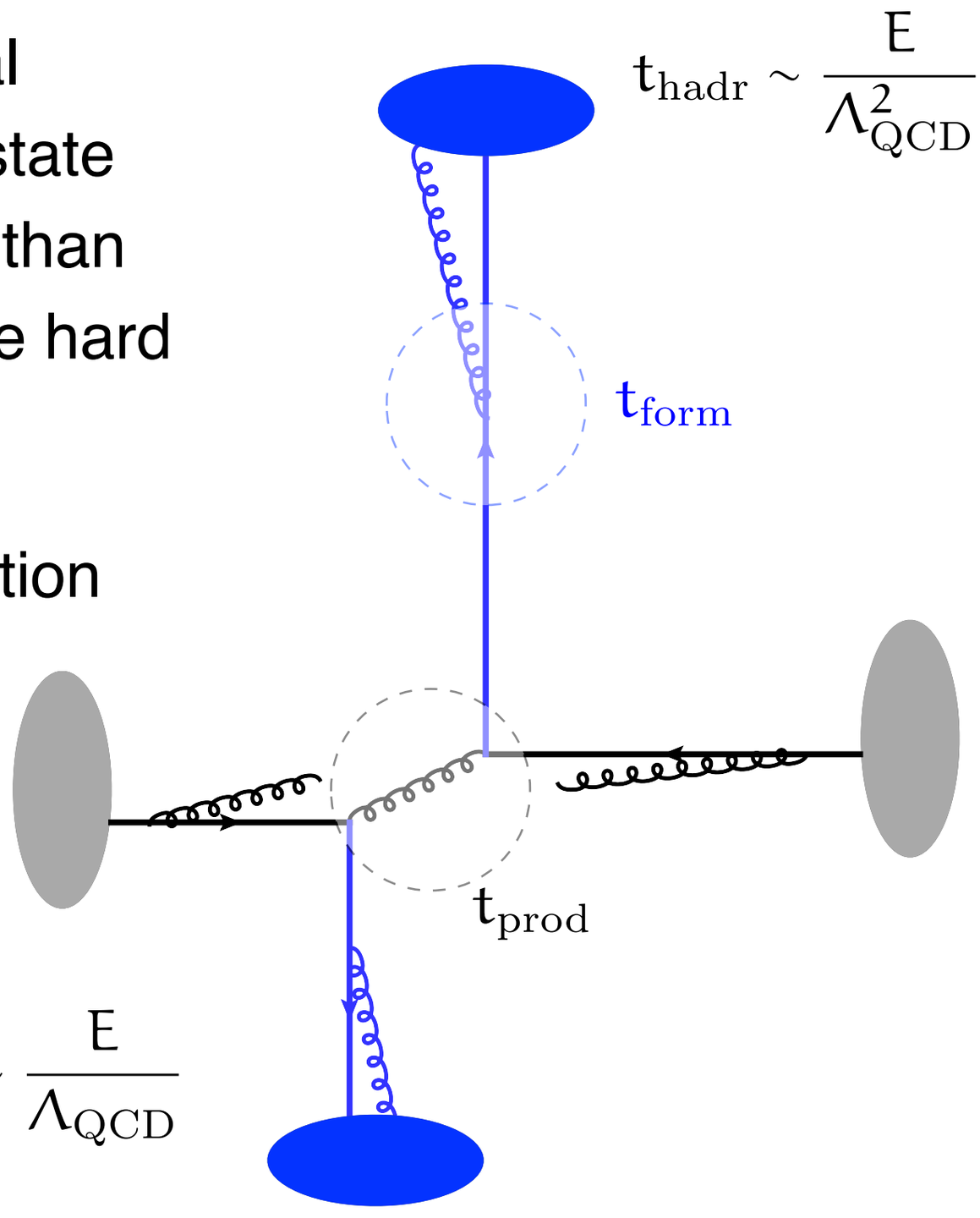
Fragmentation in vacuum (hadronization)

- At high energy hadronic and partonic observables are similar: local hadron-pardon duality (good agreement with data but doesn't say anything about hadrons!)
- Hadronization models matched onto pQCD evolution at low virtuality in Monte Carlo Event Generators: PYTHIA, HERWIG, SHERPA: Lund String model, Cluster model,…

hadronic collisions (p-p and AA)

- QCD factorization in the final state: times scales for final state fragmentations much larger than the characteristic time for the hard scattering

- Large angle soft gluon radiation dictated by color coherence



$$t_{prod} \sim \frac{1}{E} \ll t_{form} \sim \frac{\omega}{k_\perp^2} \ll t_{hadr} \sim \frac{E}{\Lambda_{QCD}}$$

In-medium fragmentation. Breaking of QCD-factorization theorem?

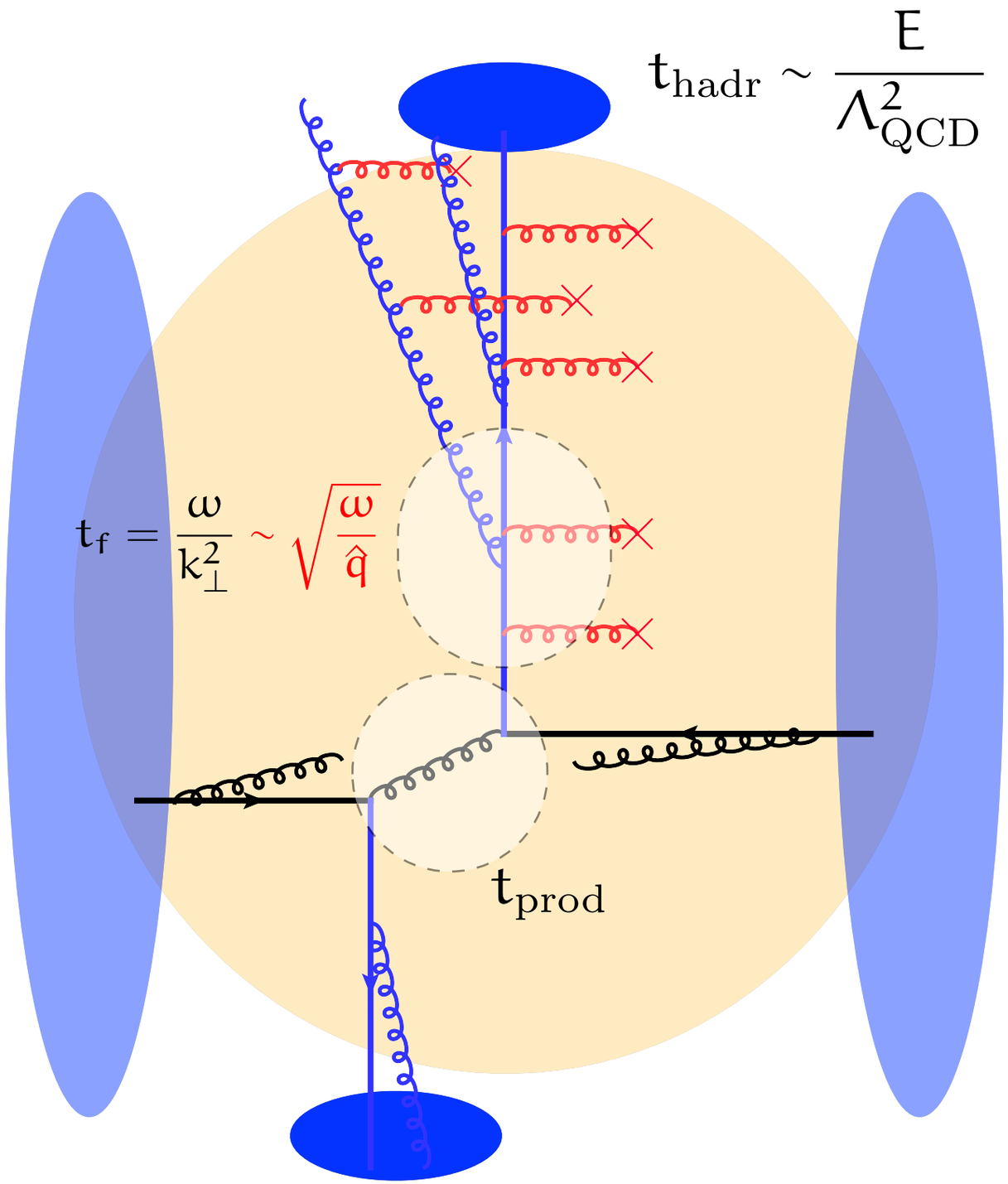
New (obvious) time scale: the medium length L

- In the presence of QCD medium:
  - Final state rescattering

$$\langle p_\perp^2 \rangle \equiv \hat{q}\, L$$

  - Coherent medium-induced soft gluon radiation: no logarithm enhancement but length enhancement

$$\omega \frac{dN}{d\omega} = \alpha_s \frac{L}{t_f} \equiv \alpha_s N_{eff}$$



[Guylassy, Wang, Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Vitev, Levai, Wiedemann, Arnold ,Moore, Yaffe (1992–2000)]

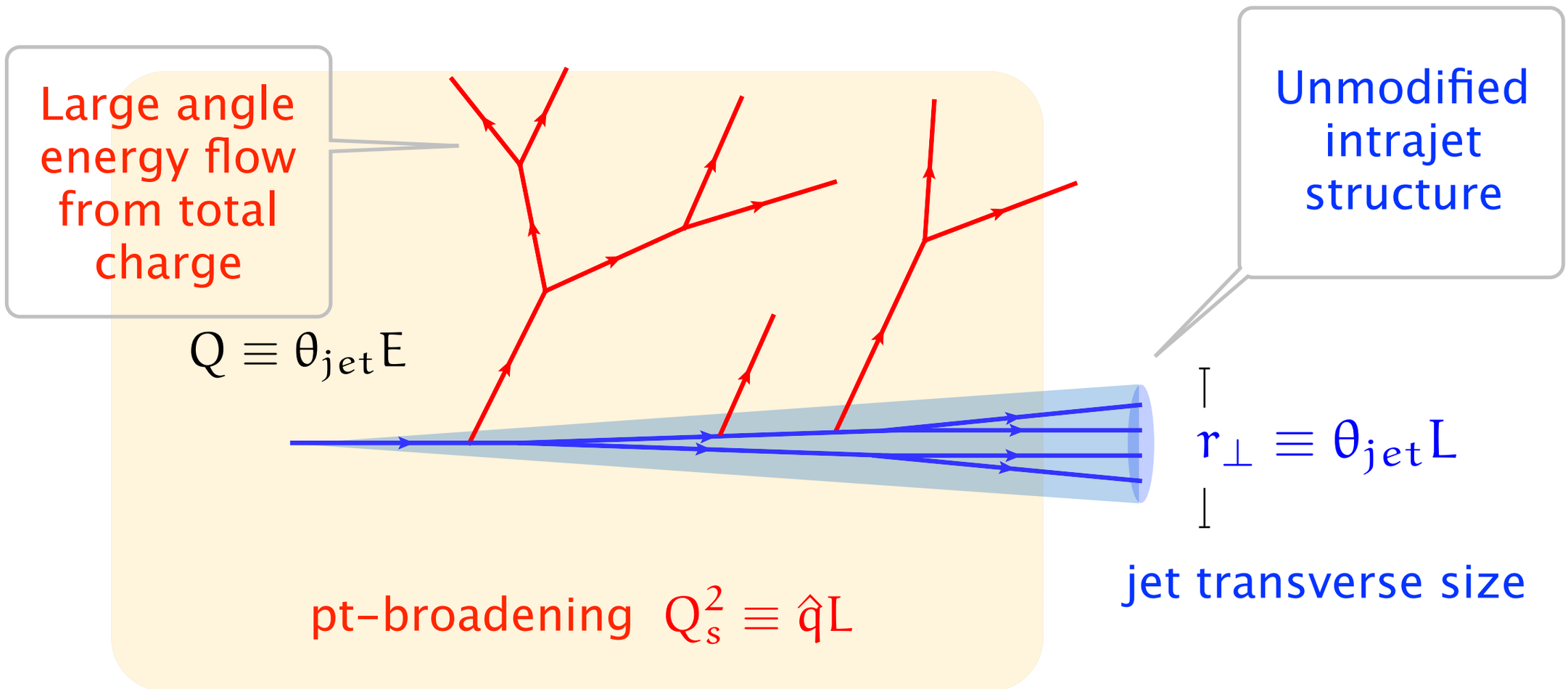
In-medium fragmentation: general picture

- Collimated vacuum cascade (triggered by the hard scattering). Color coherence suppresses large angle radiation.
- Large angle medium induced turbulent cascade. LPM effect (coherent radiation due to multiple scattering) suppresses small angle radiation

[MT, Tywoniuk, Salgado (2011-2013) Iancu, Casalderray-Solana (2012) Blaizot, Dominguez, Iancu, MT (2013-2014)]

In-medium fragmentation: general picture

- When the transverse size $r_\perp$ of the jet is smaller than medium resolution scale Q_s^{-1} the medium interacts "effectively" with the total charge of the jet (primary parton)



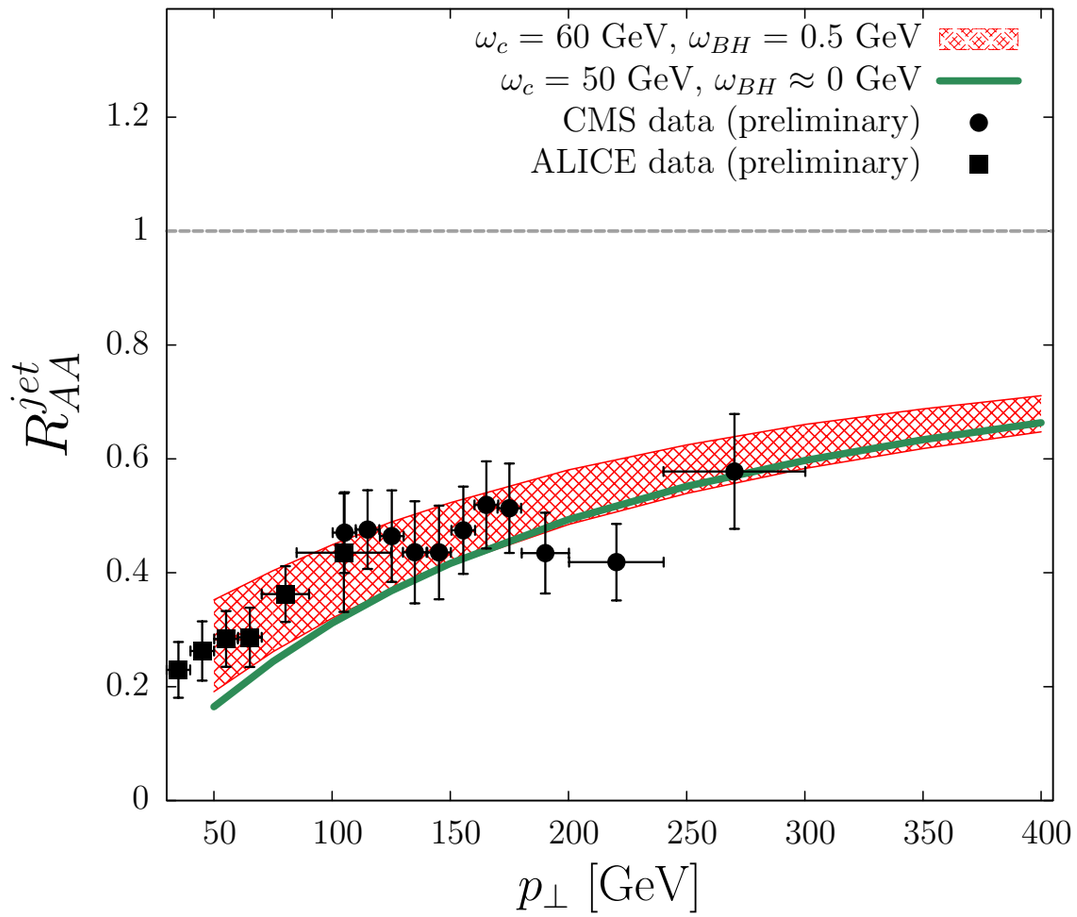
$$\theta_{jet} \ll \theta_c \equiv (\hat{q} L^3)^{-1/2}$$

- Two independent evolution variables:

$t \sim L$ in-medium cascade $\qquad t \equiv \ln Q^2 \sim \ln \theta_{jet}^2$ vacuum cascade

Jet nuclear modification factor

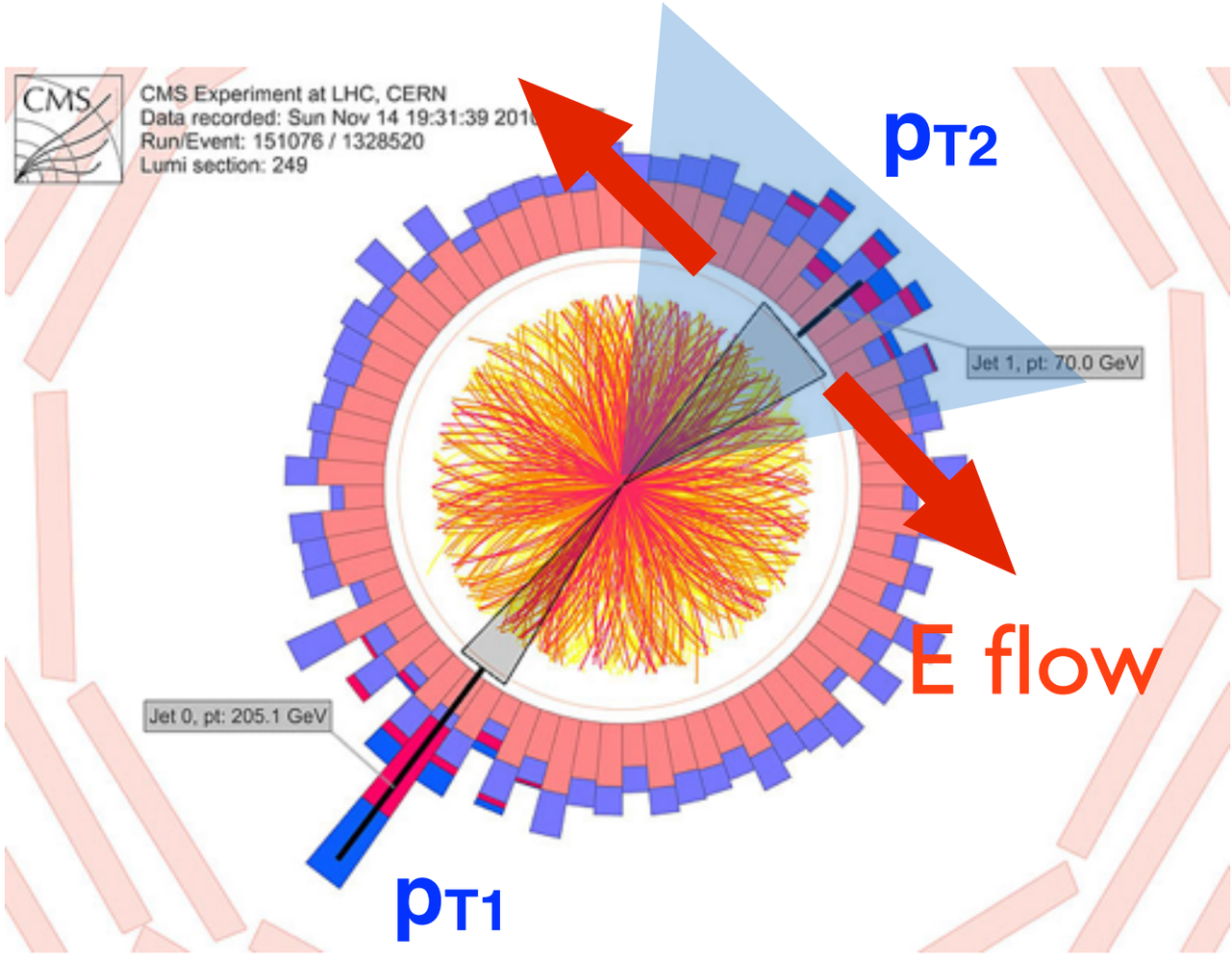
Jets or high pt partons lose energy mostly by radiating gluons at large angles: Jet in Pb-Pb collisions are strongly suppressed compared to proton-proton collisions



[MT, Tywoniuk (2014)]

Where does the energy go?

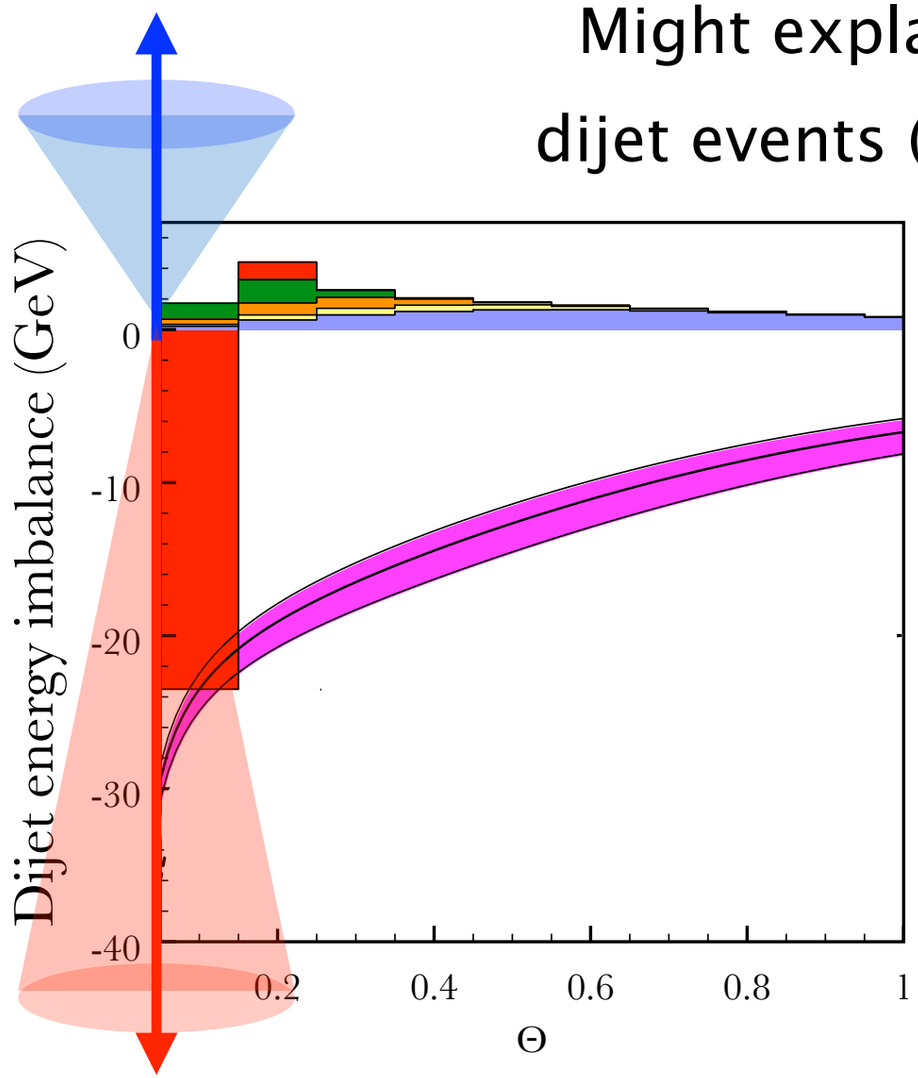
- From CMS data : the study of asymmetric dijet events at the LHC shows that energy is transported at large angles



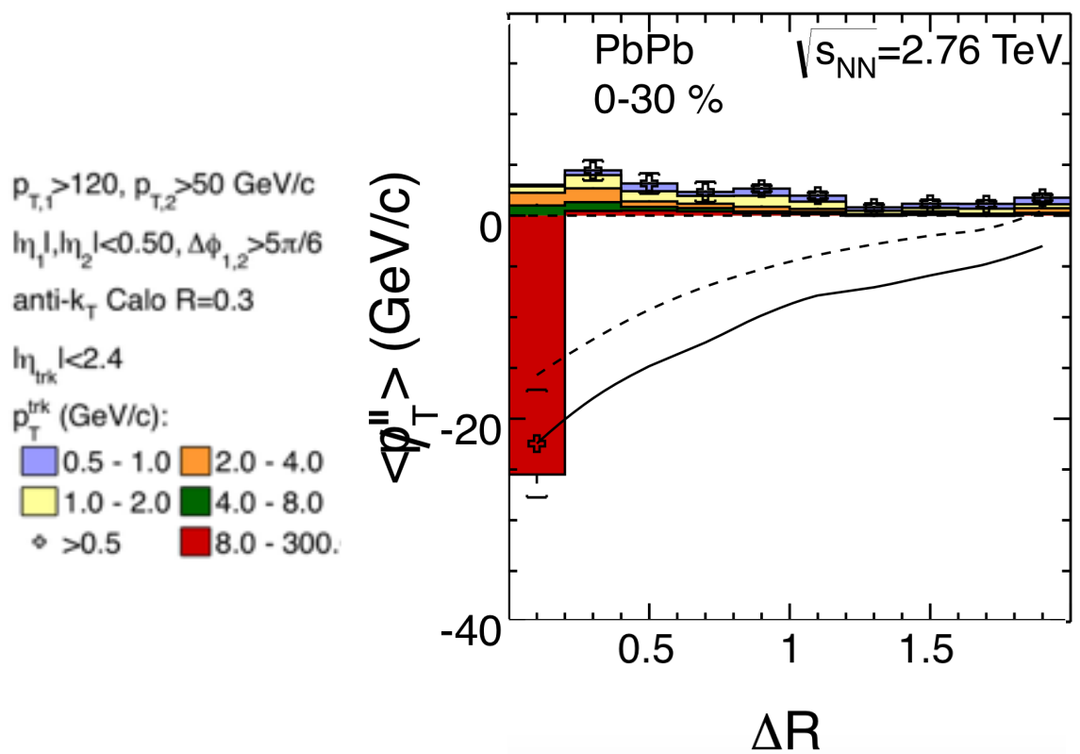
Where does the energy go?

- Turbulent medium-induced cascade $\Longrightarrow$ Constant flux of energy: Efficient mechanism to transport energy to large angles and soft particles

Might explain missing p_T in dijet events (CMS 2011-2014)



CMS DATA

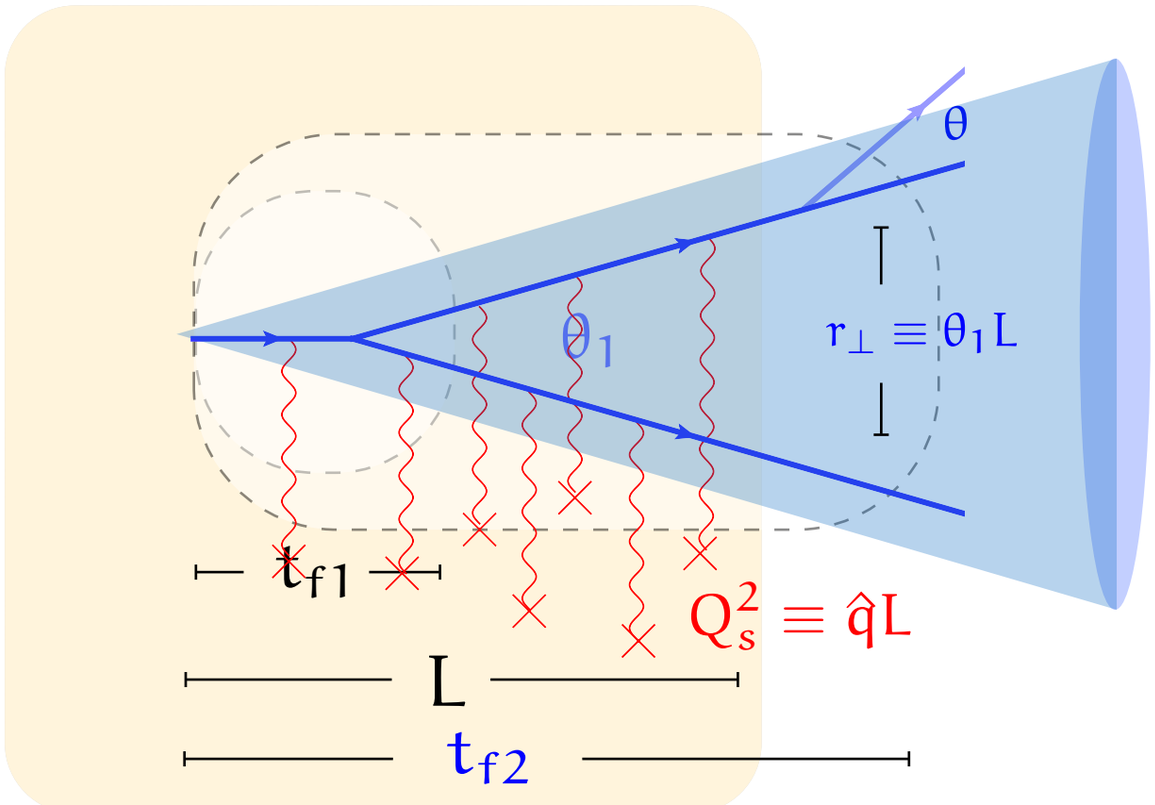


[Blaizot, MT, Torres PRL (2014)]

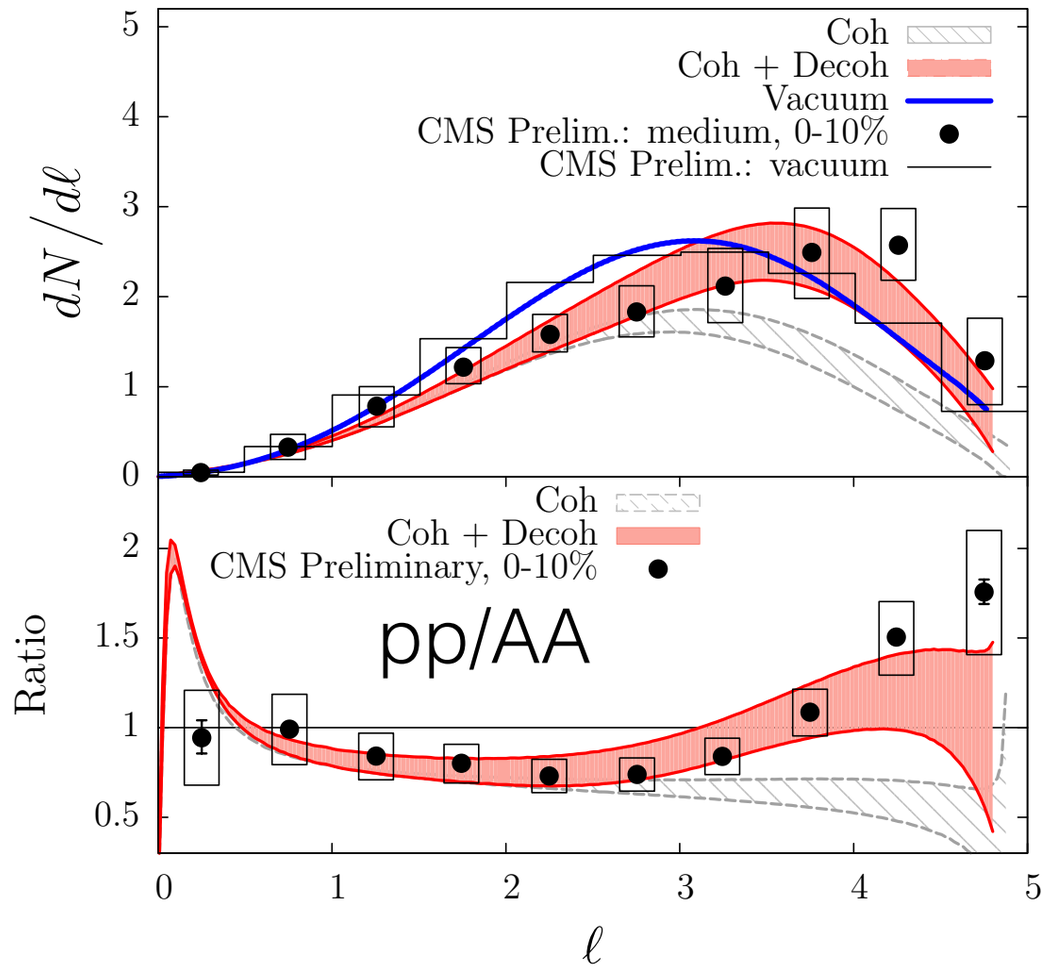
Color (de)coherence of intrajet structure

[MT, Tywoniuk, Salgado, Iancu, Casalderrey-Solana (2011-2014)]

- Consider two subsequent splittings in medium (antenna radiation pattern). In-medium color randomization suppresses color coherence opening up phase space for soft gluon radiation



[MT, Tywoniuk (2014)]



⟹ Possible mechanism for the observed soft particle excess in medium modified fragmentation functions by CMS and ATLAS

Summary and outlook

- Some theoretical results: energy loss, turbulent cascades, decoherence, etc. Not yet a robust first principle framework to calculate jet observables and quantitative predictions

- How to model the medium dynamics on top of the hard part scattering events? factorization?

- Final state interactions at the EIC: In the presence of a colored medium: color coherence is suppressed: how this feature affects hadronization models? Energy loss and momentum broadening in cold nuclear matter?

- Also study of infrared safe observables like jet shapes (better theoretical control)